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Emergence of Graphing Practices in Scientific Research

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Emergence of Graphing Practices in Scientific Research

Abstract

Graphing has long counted as one of the quintessential process skills that scientists apply independently of particular situations. However, recent expert/expert studies showed that when asked to interpret graphs culled from undergraduate courses of their own disciplines, scientists were far from perfect in providing interpretations that a course instructor would have accepted as correct. Drawing on five years of fieldwork, the present study was designed to investigate graphs and graph-related skills in scientific research. In addition to the fieldwork, a think-aloud protocol was used to elicit scientists' graph interpretations both on familiar and unfamiliar graphs. The analyses show that graph-related skills such as perceiving relevant graphical detail and interpreting the source of this detail emerges in the research process and is related to the increasing familiarity with the research object, instrumentation, and an understanding of the transformation process that turns raw data into graphs. When scientists do not know the natural object represented in a graph and are unfamiliar with the details of the corresponding data collection protocol, they often focus on graphical features that do not pertain to the phenomenon represented and therefore do not arrive at the correct interpretations. Based on these data, it is proposed that graphs are not only the outcomes of scientific research but, in important ways, constitute representations that bear metonymic relations to the research context, most importantly to instrumentation, natural phenomenon, and the mathematical transformations used to produce the graphs from the raw data. I draw on the semantics of symbolic systems for articulating competencies and breakdowns in scientists' graphing-related practices.

In the history of science, visual representations other than text in general and graphs more specifically contributed to the increasingly rapid development of science and scientific knowledge (Edgerton, 1985). It is therefore not surprising to find many such representations in scientific journals: surveys of journals in biology (Roth, Bowen, & McGinn, 1999) and physics (Lemke, 1998) revealed that there are, on average, 14.8 and 12 visual representations, respectively, per 10 pages of scientific text, of which 4.2 and 10, respectively, were histograms, scatter plots, and line graphs.

Upon seeing a graph as part of some printed materials, some individuals directly relate it to a specific situation. In the workplace, experienced people no longer distinguish between graphs and the phenomena they stand for—graphs have become transparent (Roth, 2003a; Williams, Wake, & Boreham, 2001). However, when individuals are unfamiliar with graphs, they have to engage in more elaborate processes of interpretation. From a cognitive psychological perspective, graph interpretation is a process of translation from graphs to situations and verbal descriptions; processes that translate a graph into another graph or a situation (verbal description) into another situation (verbal description) are referred to as transpositions (Janvier, 1987). Taking account of the fact that structures are relative to particular lifeworlds (Agre & Horswill, 1997), Figure 1 presents a model for the semantics based on translations and transpositions. Such a model constitutes a step toward a more adequate framework for the analysis of cognition during situated scientific activity and reasoning (Greeno, 1989; Latour, 1993).

In Figure 1, the process of interpretation, that is, a translation from graphs to situations (verbal descriptions) is denoted as Φ. (Scientific research would be characterized by an arrow in the reverse direction.) During this process, symbolic structures are mapped onto structures of the lifeworld. Janvier's (1987) transpositions within the symbolic and lifeworld domains are denoted as Ψ and μ. For example, the physicists and theoretical ecologists in my database often translated a population graph into some other graph (Ψ); they also understood a decreasing birthrate with increasing population density in terms of crowding a cage of rats (μ). The model further distinguishes between the raw materials that underlie symbolic and lifeworld structures; viewing the material world and the structured way it appears in lifeworld processes as a (dialectical) unit leads to a non-dualistic notion of sociocultural and cultural-historical practices (Leont'ev, 1978; Sewell, 1999). Thus, different transformations of the type Θ_s were involved when some scientist focused on the slope whereas others focused on the height of a graph at one or more values (Roth & Bowen, 2003). Similarly, different (experience-based) transformations of the type Θ_d led vision biologists to perceive the same cell on a microscope slide first as a "ultraviolet cone" then as a "a broken rod" (Roth, 2003a).

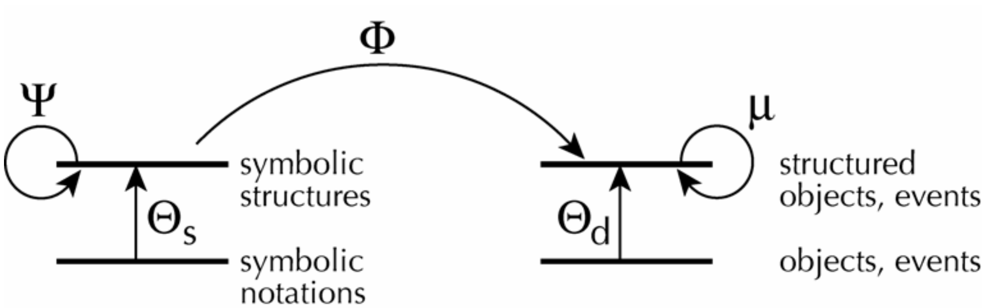

Figure 1. A classical view of the semantics of interpretation, which involves a translation of a symbolic structure into the natural world or a description thereof. (Symbols are those proposed by Greeno [1989].)

It is widely assumed that scientists are experts with respect to graphs and graphing generally and to translating them into situations and descriptions specifically (Tabachneck-Schijf, Leonardo, & Simon, 1997). It may therefore come as a surprise that experienced scientists performed much less than stellar in a recent expert-expert study, although the graphs for the interpretation tasks had been culled from or modeled on those found in undergraduate courses and textbooks of their own domain (Roth & Bowen, 2003). There was also a statistically detectable difference between university-based scientists and those working for an agency or company outside: the professors, who taught undergraduate courses in the field, had a much higher success rate than the non-university research scientists. At the same time, scientists in that study were highly competent when it came to familiar graphs. There was no difference in competence between university-based and other scientists when they explained graphs directly or indirectly related to their own work, where scientists were familiar with the methods of inquiry, instrumentation, natural environment or specimen, and so forth. These results are consistent with those of cognitive anthropological studies of arithmetic, which show that people may be highly competent in everyday settings while failing to solve structurally equivalent school-like paper-and-pencil tasks (Lave, 1988; Saxe, 1991; Scribner, 1984). This suggests that rather than being context independent, graphing (and arithmetic) competencies are tied, at least in some aspects, to familiarity with the setting (process of construction) and the phenomena represented. Competent graph reading may involve a dialectic process Φ_2, whereby symbolic and familiar phenomenal worlds mutually constitute one another (Figure 2).

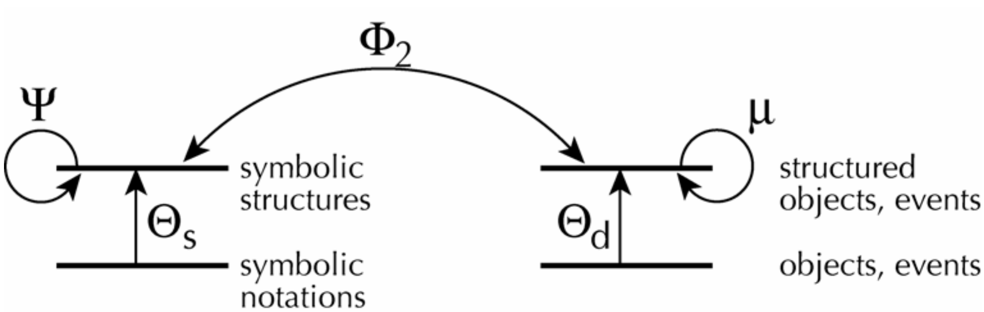

Figure 2. Dialectical view of semantic processes underlying competent performance.

In the past, cognitive deficit has often been used to explain the performances of students and laypeople on science and mathematics related representations (e.g., Leinhardt, Zaslavsky, & Stein, 1990). However, given that all the scientists in the expert/expert study had been successful in their careers (i.e., publication rates, grants, scholarships, or awards), a deficit model appears inappropriate. A different approach to the performances relative to scientific and mathematical representations focuses on graphing as practice (Roth & McGinn, 1998), which requires a different methodology for studying how scientists know and learn mathematical representations. It has therefore been suggested that to understand graphs and graphing in science, we need to move toward a cognitive anthropology of graphing (Roth, 2003b).

In the present study, I use materials from a study of ecologists at work to exemplify the results of my ongoing research regarding the emerging graph-related competencies of scientists during their research. Over the past five years, I have conducted several ethnographic studies of graphing in scientific research (laboratory, field) and at a variety of workplaces (farm, fish hatchery). I have also asked 37 research scientists in think-aloud protocols to interpret graphs from introductory courses and textbooks in ecology. The present study was designed to gain an understanding of how graphing practices (skills) emerge in the process of scientific research, that is, how the function Φ_2 (Figure 2) arises from and comes to be established in everyday scientific practice. I was further interested in the relation between scientists' structuring Θ_d of their lifeworlds (phenomenon, instrumentation, research methods) and the corresponding structuring Θ_s in the symbolic domain (e.g., variables used). Here, I present and analyze both the think-aloud (un/familiar graphs) and fieldwork data (emergence of graphs) in a case study pertaining to the same scientist.

Research Design

Sites and Participants

My studies of graphs and graphing among scientists, technicians, and other professionals began in 1996. Two separate studies involved a total of 37 scientists in think-aloud protocols interpreting graphs provided to them; one study focused on ecologists (n = 16), the other on physicists (n = 21). Most of the scientists already had obtained a Ph.D. degree; some of those with M.Sc. degrees were in the process of obtaining one. All had a minimum of six years of experience in doing independent research. They were highly successful in their field, both in terms of recognized publication records and funding they obtained. Because of the marked differences of the interpretative processes and success pertaining to familiar and unfamiliar graphs, I have conducted, so far, four separate ethnographic studies focusing on mathematical representations generally and graphing in particular. These studies take/ took place in the following contexts: in environmentalist group, which included a farm and its technicians (1998–02); a fish hatchery (2000 to date); ecologists in the field and on campus (1997–2000); and an experimental biology lab (2000 to date). In the present article, I draw on data collected among ecologists.

Data Collection and Modes of Participation

A cognitive anthropology of graphing examines the many ways by means of which representations (inscriptions) are gathered, combined, tied together, transformed, etc. (Latour, 1987). As part of my research, I observe and videotape scientists and technicians as they do their normal jobs; I conduct interviews concerning aspects of this work and the operation of their workplaces more broadly, keep observation notes, and photograph people, places, and objects. I collect (copies, photographs of) artifacts produced as part of the ongoing work and any subsequently presented or published outcomes of the work observed, such as research articles and dissertations. All documents are digitized (if not already in this form), imported into Word or Acrobat and annotated as a way of providing image-enhanced reports from the field. Alternatively, especially when there are many images or large image files requiring a lot of computer memory, the html format is chosen for the production and maintenance of field notes. I regularly interview individuals from other activity systems, such as research scientists and support biologists, who interact, collaborate, and exchange information with those under study. All interviews are transcribed in an ongoing manner, as soon as possible after they are recorded. In addition to the observational fieldnotes, theoretical and methodological fieldnotes are constructed and added to the database in an ongoing manner.

I draw on different modes of participation to learn about the practices in the respective sites, which most frequently takes some form of apprenticeship as an ethnographic fieldwork method (Coy, 1989); during the period of negotiating access to a particular site, I offer to serve as a helper or (field, laboratory) assistant. Participation in the ongoing work with the purpose of getting the day's work done allows a new participant in a practice to acquire the familiarity with relevant objects and events that characterize the members of the particular community of practice. Working as an apprentice or as an assistant in everyday work practice provides a perspective from within the culture; it particularly yields an understanding for the temporal constraints of the practice that are unavailable to the fly-on-the-wall observer participant. The fundamental assumption underlying this research approach is that one cannot truly understand a particular "form-of-life" unless on participates in it (Wittgenstein, 1958).

Formal Tasks

For the think-aloud protocols, I constructed three types of graphs that are very common in introductory ecology courses at the university level, featuring (a) three distributions, (b) a conceptual model (e.g., Figure 3), and (c) a conceptual model with two independent variables (isograph). (Description and cognitive analysis of these graphs can be found elsewhere [Roth, 2003b].) For the study involving physicists, I used these graphs plus a set of structurally equivalent graphs in a physics context. During fieldwork, I employ these graphs to each scientist with respect to the entire database but select additional graphs that are appropriate to the situation in terms of content and context. For example, during the fieldwork among ecologists, I used graphs from various introductory textbooks that portrayed population dynamics and predator-prey relationships in various forms. The ultimate purpose of using a variety of graphs directly and indirectly related to the participants' work is to tease out the role of familiarity and experience in graph-related competencies.

Data Transformation and Interpretation

The videotapes are transcribed in their entirety, including video images of important moments that cannot be understood without the photographic reference to the situation (or would require complex verbal description). The videotapes are digitized to make them available to frame-by-frame analysis and production of high-fidelity transcripts, including, where appropriate, pauses, overlaps, and emphases. Video offprints are inserted in the transcript to make salient those features that the participants referred to in an indexical manner, for example, by pointing. As a first step in the analysis, the transcripts are carefully annotated and analyzed using the highlight and comment functions of my word processor; this analysis proceeds slowly and from a first-time-through perspective aiming at a description of events as these would have been evident to participants at that moment and without the benefit (of their or my) hindsight. These annotations provide additional information required for understanding a particular sentence or event, and which is collected as data and available elsewhere in the database. During subsequent passes through the materials, emergent categories are related to one another and to theoretical concepts; the written analyses are kept in dated files, providing an audit trail that documents the emergence of grounded theoretical concepts (Strauss, 1987).

Fieldwork Context

The present study draws on data collected over a three-year period among ecologists, which involved serving as a research assistant in an ecological field research camp in a mountainous area of British Columbia. There, I assisted one research group by hunting and capturing lizards, skinks, rubber boas, and garter snakes and conducting measurements in the field and field laboratory. My main informant was a doctoral student (pseudonym Samantha) in her fourth through sixth years of doing independent research; her work was partially funded by different organizations interested in the topic of her research. My database is extensive, consisting of observations recorded in fieldnotes, photographs, audiotaped conversations in and about fieldwork, videotapes of data collection in the field and field laboratory work, and formal interviews conducted during the winter months, which Samantha spent on her home campus. The database further includes a complete set of Samantha's laboratory notes from 1996–97, her dissertation, and the articles and reports published to date based on this work. There are also videotapes of poster sessions at local and national conferences, videotaped talks about her work in university seminars, and all slides and notes used for these diverse presentations.

Among her peers (graduate students and professors), Samantha stood out in her ability to understand mathematical representations and to do statistics. Her undergraduate background was in mathematical biology, and she repeatedly taught a fourth-year undergraduate course in statistics. She extensively used multivariate statistics and was known in the department as a "statistical wizard."

The purpose of Samantha's research was to (a) describe the natural history of a particular lizard species (e.g. body size, habitat preferences, movement patterns); (b) determine basic life history traits (e.g. life span, survivorship, and litter size); and (c) identify the fecundity and survival costs of reproduction. Samantha conducted her research at the northern-most boundary of the area where the particular species was believed to occur. Although southern relatives of the species had been researched by others on occasion before, very little was known about this species. Samantha drew on research on other reptilians for ideas about how to capture life history information, but also thought that there were particular adaptations that her subspecies must have undergone to be able to live so far north. Finding out how to represent the lizard and its environment was central to her work. Her task, therefore, was one of bringing order to this lizard species and the lizards' lifeworld without knowing beforehand what that order might be. This, as I show here, involved becoming intimately familiar with the phenomenal world and structuring it in common (e.g., temperature) or new and not so common ways (distance of capture site to a rock pile, bush, forest edge); these structural aspects of the setting then became starting point for her statistical analyses.

Interpreting Un/Familiar Graphs

Previous research showed that research scientists were moderately successful in providing interpretations of graphs that a professor in introductory ecology would have accepted as correct (Roth & Bowen, 2003). In this study, I first present results from the think-aloud sessions with Samantha pertaining to un/familiar graphs and, in the next section, describe how a particular graph (featured in her dissertation and published article) and the related variables emerged from her fieldwork.

Talking about an Unfamiliar Population Graph

Although she was teaching statistics at the undergraduate level while completing her doctoral work, Samantha made many of the same errors that were characteristic of non-university scientists. I had asked her to interpret a total of 8 graphs from an undergraduate textbook (Ricklefs, 1990) and all were typical for the type of graphs that appeared in ecology textbooks and courses more generally.

The following transcript from the end of the session concerning a graphical model (Figure 3)—a type of graph that became prominent in the discipline during the 1950s and 60s (Kingsland, 1995)—shows some of the characteristic features of graph interpretation sessions.

> [i] I don't really know, I'm not sure. I think they're probably, that's why I was wondering if that's [P_2] an unstable equilibrium point, if it drift this way [S_3], then it's just gonna crash eventually, which is gonna be a bad thing. [ii] So for conservation of species ((gestures from P_2 toward S_3)) you potentially don't want to get above this limit [P_2]

> because the population will essentially crash. [iii] If the birthrate declines so rapidly ((gestures b from P_2 into S_3)) above that certain point, I expect that it will probably crash, so you'd want to keep it in this region right here ((points to P_2)), because I expect, I expect they're both ((points to P_1, P_2)) unstable equilibriums in which case outside of these points ((gesture from P_1 into S_1, P_2 into S_3)) the population essentially will crash very, very quickly. [iv] So, yeah, I'd keep it in here ((gesture outlining S_2)). [v] There're all sorts of models that have been developed about harvesting relative to carrying capacity ((points to b_{max})) and all that's kind of stuff, because this [b_{max}] is probably perhaps not unlike– [vi] Well, there's been some stuff done, actually I saw a paper not that long ago that looked to see if the cod populations on the East Coast were suffering the Allee effect. [vii] So there is this problem ((encloses S_2)), that if you get too low [P_1] or too high [P_2] essentially you got a crash and so they tried to working that in, when they work out harvesting strategies. (INT JUL 30, 1997, p. 5)[1]

In the derivation of the logistic model, it is assumed that, as N increased, birth rates declined linearly and death rates increased linearly. Now, let's assume that the birth rates follow a quadratic function (e.g., $b = b_0 + (k_b)N - (k_c)N^2$), such that the birthrate and death rate look like in the figure. Such a function is biologically realistic if, for example, individuals have trouble finding mates when they are at very low density. Discuss the implication of the birth and death rates in the figure, as regards conservation of such a species. Focus on the birthrates and death rates at the two intersection points of the lines, and on what happens to population sizes in the zones of population size below, between, and above the intersection points.

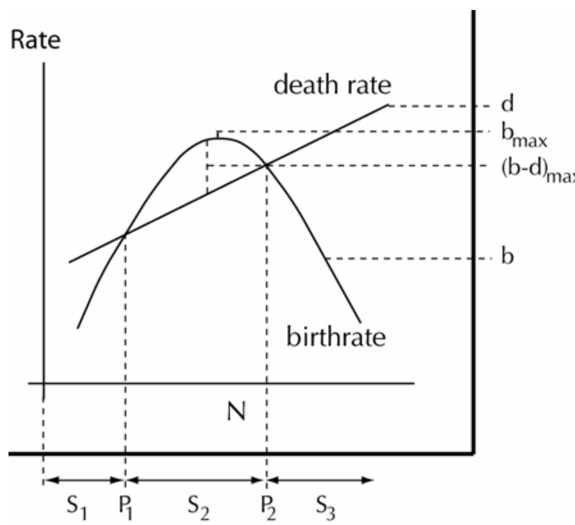

Figure 3. Graphing task as presented to Samantha; markers and labels of specific features have been added here for analytic purposes outside of the border.

In this transcript, Samantha made reference to a number of concepts that are stable features of the discourse in the ecology community—including "unstable equilibrium" ([i]) "carrying capacity" ([v]), and "Allee effect" (vi).[2] She also drew on her memory of

[1] All data presented here are referenced to their source in the database, date, and page (photo) number, where applicable: FN = field note; AT = audiotape; INT = interview; PH = photo; DISS = dissertation; SAM = Samantha's field notebook.

[2] The Allee effect pertains to the trouble of finding mates when the density of a population is low.

recent events, such as a paper discussing the (in Canada hotly debated because economically salient) crash of the cod populations on the east coast generally and in Newfoundland more specifically ([vi]). This reference to a specific population exemplifies another recurrent feature in my database: when facing a graph that they were unfamiliar with, scientists articulated concrete and familiar phenomena even if it did not pertain to the situation explained by the graph (e.g., in the case of a plant distribution in southern Texas, they talked about mountains in British Columbia). Their interpretations were not inferences from the graph to some natural phenomena, but rather developed situations in a dialectical fashion from the interplay of the graph at hand and the world that they were familiar with.

In saying that the population would crash if its size was larger than P_2 ([i], [iii], [vii]) Samantha completely misinterpreted the second intersection point of birthrate and death rate graphs, the central feature of the graph. She said that it was an unstable equilibrium ([i]). However, the population is in a stable equilibrium at that intersection, because the pressure on the population on either side of P_2 is toward the size P_2 at the intersection (see Figure 3). How can we explain what has happened? If one assumes a static picture, where the graphs depict different values of each rate, then the population would crash in S_3, where the death rates are larger than the corresponding birthrates. The correct interpretation, however, requires the graph to be seen dynamically: at any one point in S_3, there is a decrease in population. A change in population entails a change in birthrate and death rate, so that the next state of the system has to be calculated with new these values. That is, Samantha—as a number of her peers—did not attend to the fact that the birthrate and death rate are functions of population size (or density), which, in the case of the birthrate, is explicitly stated in the caption in mathematical form (Figure 3).

In this episode, Samantha committed a second error common to nearly all scientists ([v], [vii]). It pertained to the question of that population size, where the increase in individuals would be a maximum. All but one participant suggested either the population where the birthrate has a maximum (b_{max}) or where the difference between birthrate and death rate $(b - d)_{max}$ has a maximum (Figure 3). A third error in this transcript pertains to the carrying capacity ([v]): it is not the population where the birthrate is at a maximum but to that population size that the logistic growth curve asymptotically approaches—here the intersection P_2.

The example used here is of particular importance, because the intersection P_2 is of the same structure as the intersection of supply and demand graphs in simple economic models. Such a graph was used in an expert study of graphing, leading to the development of a computer model of expertise (Tabachneck-Schijf et al., 1997). The sole subject in the study, however, was Herbert Simon, a trained economist, familiar with the stereotypical rather than paradigmatic representation of prize as a function of supply and demand curves. That is, despite teaching undergraduate statistics courses and despite being an ecologist, Samantha misinterpreted a graphical feature that was used as a paradigm case in other studies on the cognition of graphing.

Talking about Familiar Graphs

When scientists talked in interview situations about graphs from their work, they invariably articulated the context of their laboratories, the phenomenon of interest, and matters of instrumentation before they actually began to explain what some graph was intended to express. Furthermore, their intimate familiarity with the contextual detail of the situation—from which the data were abstracted that ultimately led to the graph—allowed them to provide plausible accounts for anomalies. This was also the case in the graph interpretation sessions with Samantha.

The following excerpt derives from an interview to which Samantha brought the graphs that she had presented at a recent conference. Asked about the data that seemed to be some distance from the others (A and B in Figure 4), she began talking about the data point as expressing “a really short tail,” and then continued to explain that she did not think to have “ripped off” the tail of a female lizard during the 1996 season (the interview was in March 1998). Lizards are capable of tail autotomy, that is, they can shed their tails or part of them in situations of danger even without a predator (or an ecologist) getting a hold of the animal at that body part. (It has happened to me repeatedly that I ended up with the tail of a skink rather than with the animal itself.) Samantha did not recall having had such females during this particular season, though in her other seasons, she has had such specimen. That is, the data point not only represented a short tail but possibly a lizard that had lost the tail prior to capture or as part of Samantha’s current research. Here, a graphical feature was directly linked to the particular case of one lizard rather than lizards in general.

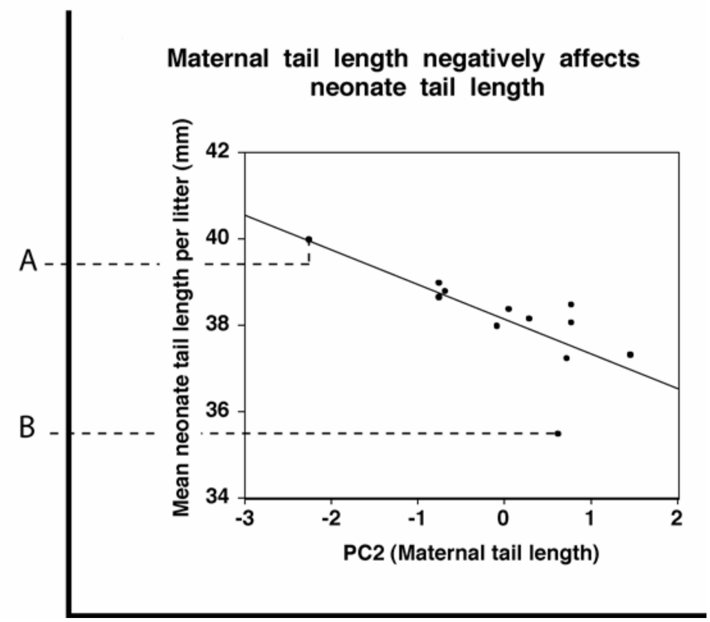

Figure 4. Graph featuring intermediate results from Samantha’s research, which she had presented at an international conference. (ASIH slides, JUN 26-JUL 02 1997)

> A really short tail, I don’t know who she is, this, I don’t think in 96 I’ve ripped anybody’s tail off, I don’t think. I don’t know who she is actually but yeah she’s got a very, very short tail. Yeah, and she didn’t do, she had most, oh I think she is that problem child. I had one female that, she still looked like she hadn’t let all her kids out. She had like two kids or something and one was dead but she still looked pregnant like but she wasn’t

> cooperating. I don't know if she had just decided that she was too stressed out and she didn't really want to let it all go. So, that might be her, actually. (INT MAR 12, 1998, p. 15)

Initially, Samantha appeared uncertain about the specific animal, but then remembered a "problem child," a female that looked as if she had not given birth to all her offspring. She recalled that the particular female had two kids and that one of them was dead. Samantha also drew on local knowledge when she considered what to do with the data point that potentially was an outlier (Figure 4, points A and B). Again, It was Samantha's knowledge of the contextual details, here the measurement accuracy, which provided her with a resource to approach the situations.

> Hum, I would take that [Figure 4, A] out and see if, well obviously if I take that [Figure X, B] out it's gonna hold, I would take that out and see if it holds or take both out and see if it holds. I guess I don't, I'm not that knowledgeable about all the statistics behind outlier analysis. From my perspective, if I have a good reason of throwing it out, I'd throw it out. But generally I don't. I would look to see if it's one point that's driving the whole relationship and if, then that's probably not real. And in this case, that's probably the case, I don't think. I think that's within measurement error. I mean, without that point [B], I'm looking at differences from 38 to 40, which is nothing, like zilch. It's 2 millimeters; I can't measure that accurately. So, I think that one's [graph] bunked too. (INT MAR 12, 1998, p. 13)

Samantha did not just accept a statistical correlation but considered it under the aspect of outliers and the source of the variation and whether it might affect the entire analysis. She then evaluated whether these variations that have their source during data collection. In the present situation, although the relationship between the two variables was statistically reliable, she ended up doubting that the relationship was real but that it had arisen by chance. Out of context, such as if it would like had it been used in an interview of graphing, the graph looks like it represents a real phenomenon. All but one data point lie close to the regression line. Yet there is potential for the correlation to be spurious, and Samantha intuitively knew this while talking about the graph. The total variation in the tails of offspring amounted to 4 millimeters, but the variation was only about 2 millimeters if the two points [A, B] were for some reason variations in her measurement. She knew that she could not measure the tail length as accurately as 2 millimeters. To understand, we have to look again at how this aspect was measured in the field laboratory. Because lizards moved about resisting the measurement, they were placed in a plastic box and squeezed, using a foam pad, against the transparent bottom. Using a felt marker, Samantha drew a line onto the bottom of the box following the center of the lizard (Figure 5a,b). To limit stress levels to the animals and to decrease the probability of having tail autotomy during the procedure, Samantha did not attempt to straighten the lizards. Rather, she used a map-and-plan measure, which, when its wheel was rolled along the trace, provided a measurement of its length.

In the present situation, Samantha was not even talking about the measurement process, but the variation in measurement was present in her talk as tacit, unarticulated background that correct interpretations nevertheless require (Barwise, 1988). But when asked specifically, she did articulate such features. That is, when looking at the graph, she understood the variation of the entire dataset as falling within the range of variation in individual measures. Therefore, the correlation was potentially spurious and subsequent data points might well change the situation.

a. b.

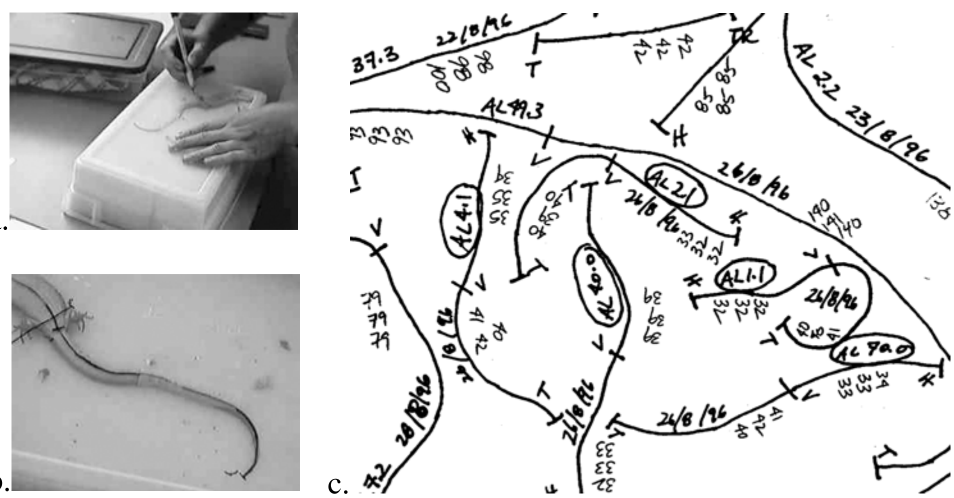

Figure 5. To determine the length of a lizard, it is placed in a plastic box with a transparent bottom, so that its centerline can be traced onto the box. The lines are the transferred to a sheet of paper (right). In the representation to the right, one can see (a, b) that lizards do not lie in a nice straight line to allow measurements with a ruler and (c) that repeated measurements exhibit variation of up to 2 millimeters. (PH 73, 74, JUL 04,1997; field notebook 1996)

Samantha talked about the graph but the embodied knowledge related to measurement process and products constituted a tacit background against which any interpretation of the graph stood as figure. There was a switching back and forth between considering the correlations as an expression of knowledge about the species, and the intimate knowledge about individual lizards that contributed to the data. Repeatedly, she remembered individual specimen (e.g., "Bertha" was "really pregnant" and had a large litter). Furthermore, in another situation, where she had wanted to make repeated measurements from the same animals without being prejudiced, it turned out that she knew from which cage the laboratory assistant had taken each lizard. Thus, although she attempted to conduct repeated blind trials, she actually knew each individual when a lab assistant brought it for another measurement. Finally, Samantha was also aware of the problem with the small number of data points, but there was little that she could have done about it. For the entire season of 1996, she had only 12 females that gave birth in the laboratory after having been captured. As her dissertation topic concerned, in part, costs and trade-offs during reproduction, she had to work with the amount of data that she could get.

Discussion

Samantha's interpretation of the population crashing in S_3 (see Figure 3) is an error in an action of the type Ψ (Figure 2) because the consequence of the condition $b - d < 0$ has not led to a transformation of the state into one where N decreases. Furthermore, she answered the questions about the population size (density) at which the increase in individuals is largest by looking for something consistent with "largest," structuring the graphical display (Θ_s) perceptually such that b_{max} stood out, which led her to the conclusion that this situation is the case when the birthrate is at a maximum. Other scientists structured the display (Θ_s) such that $(b - d)_{max}$ stood out. Samantha made an attempt at a translation Φ to the phenomenal world when she talked about the situation of the cod on the east coast of Canada.

Problems of transformation at one level have repercussion in that the scientists generally put into question the transformation processes at another level. Thus, when scientists ran into contradictions during their interpretations, they made comments about having to look at the graph in a different way—for example, they shifted from looking at the height of a graph at a certain abscissa value to its slope, and vice versa (Θ_s). Or, while attempting to relate natural populations to the graph (Φ), they began drawing new configurations of it with three or more intersections between birthrate and death rate graphs to create equivalence between the two levels. That is, they engaged in transpositions Ψ to assist them in better comprehending the graph before them.

The data presented here suggest that the semantics proposed by Greeno (1989) are not appropriate to model graph interpretation. This can be seen from the fact that Samantha—as many scientists in my study—experienced difficulties relating common graphs from textbooks in her own domain to anything that she was familiar with, and on the other hand, the fact that she provided a lot of contextual information from the research before talking about her graphs. Rather, there is evidence that scientists are successful then when a function Φ already exists or when it can be established because scientists are already familiar with some phenomenon that has the potential to fit. They substituted familiar instances even in cases when the data represented came from specific circumstances. In such cases, the process of interpretation therefore involves a mutual constitution and stabilization, from the symbolic to the phenomenal domain and from the phenomenal to the symbolic domain. These results contradict the contention that people "extract a great deal of quantitative and qualitative information (indeed, virtually the same information) when a graph has no labels at all" (Pinker, 1990, p. 93). To the contrary, problems in interpretation emerged exactly then when the participants had trouble with the labels, meaning, for example, that they could not relate it to *specific* natural phenomena and data acquisition procedures that they were familiar with.

How Rock Size and Rock Thickness Become Natural Historical Descriptors of Alligator Lizards

In the second part of the previous section, I showed that Samantha understood her graphs, because she understood the animals through the long-term exposure to the same natural and climatic environment; and she understood the animals because she understood the graphs. In this section, I describe the mutual constitution of structures in the natural and symbolic worlds. That is, I describe the emergence of the function Φ_2 (Figure 2) in the course of doing scientific research. I also describe the emergence of the functions Θ_s and Θ_d, that is, how symbolic and phenomenal world took on their structured aspects. As part of her fieldwork, Samantha began to tune to even small changes in the environment where she found lizards and differences in the capture location over time. What she noticed was often not very explicit and clear, it was more of a gut feeling. Some of the things that she guessed at did not pan out to give significant relationships—these did not show up as structural elements in the symbolic representations (Θ_s). The variable “distance to nearest rock pile,” which emerged in the course of her research, was subsequently discarded but “distance to the nearest rock” was reported, and the tie between temperature and rock size emerged and was retained. In the following sections, I provide an account of the emergence of structures in Samantha’s phenomenal and symbolic worlds.

How Rocks Become Salient

In the model used here (Figure 2), the structuring of the natural world is an important component of understanding structures in graphs (symbolic domain). In Samantha’s work, what the relevant life and natural history variables would be was unknown at the start of the project. In fact, the purpose of the project was the identification of salient structures. That is, how to structure (look at) lizards and their natural environment (Θ_d) was not evident but was the result of the research. According to existing texts, lizards in this geographical region can be found most easily under “rocks, logs, and other cover objects” (Gregory & Campbell, 1984, p. 50) and “bark, inside rotten logs, and under rocks and other objects on the ground” (Stebbins, 1966, p. 136). Such descriptions are not necessarily salient in the actual research process—whether an “optimal search strategy” includes rotten logs, for example, is something that emerges from the research process itself. It may, in fact, turn out that it is not worth the scientist’s while to look in some areas and under some structures.

At a kink in the trail 40 from the car, Samantha turns sharply to a pile of rotting logs (6 or 7) that lie to the left of the bend and starts turning them over while saying you have to look under (photo). […] Log after log is flipped and replaced. No lizards. […] This particular patch of wood pieces was of more interest to Samantha than isolated pieces of smaller wood. (FN JUL 6, 1997, PH 06 JUL 04, 1997)

Samantha ended up searching mostly “under rocks, because there isn’t wood in the area, though I have found both lizards and snakes under wood. Any cover object if I can move it without wrecking things too much and I can for sure get it back in its place” (AT JUL 4, 1997). Nevertheless, she continued to “wander around and flip rocks although there’s some systematic strategy to the whole thing. But in addition to that it’s good to sort of try and keep eyes and ears peeled. It takes a while to sort of develop the search image” (AT JUL 4, 1997). At that point (second year of research), it was not yet clear what role the rocks might play in the description of the natural history of this alligator lizard species but Samantha raised the possibility of rock size making a difference: “But um, yeah, one of the things I find is the size of rock you find them under so it would sort of skew things if I only looked under one size [of rocks]” (AT JUL 4, 1997).

The salience of “rock” to the research on the lizards was subject to some familiarity with the species in the field. Samantha had gathered such experience by spending several weeks during the previous year with her supervisor on various slopes in a mountain valley seeking and capturing these animals (without being able to fully articulate where, when, or under what conditions she would most likely find them). In the process, she began to notice particulars of the circumstances when and where she saw and was able to capture these lizards. Rocks and rock assemblies (Figure 6) were among the features about which Samantha collected information, though the second ones did not enter the research as a category until the end of Samantha's second year in the field. When she came across lizards, these headed, among others, for rocks under which they disappeared. In the process of "messing around with habitat, thinking about some ideas" (INT MAR 26, 1998, p. 20) during her first field season (1996), how far lizards had to run emerged as an intelligible and plausible natural history variable. As part of her work, she needed to establish whether the variable was useful (fruitful) in the course of her work.

a. b.

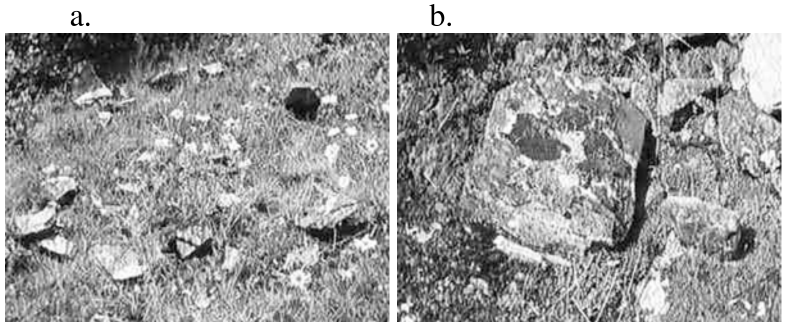

Figure 6. a. Typical site for hunting lizards, with rocks of different sizes strewn all over. b. Rocks larger than 10 centimeter across are turned over and, if a lizard is found and captured, measurements (temperature above, underneath, size, thickness) are taken. (PH 16, 17, JUL 04, 1997)

The variable "distance to the nearest rock" did not occur by itself. Rocks were salient in other ways as well. Thus, while working with an undergraduate research assistant, during her second field season, a sense emerged in their interactions that it might matter whether the nearest rock was standing alone or part of an assembly of rocks. In the course of a day's work, they evolved a new category and an associated operational definition: a "rock pile" has fifteen or more rocks touching one another. In most instances, however, Samantha and her helper did not count how many rocks there were in an assembly but glancing at the structure established whether it was to be counted as a pile. Other aspects of rocks became salient as Samantha conducted her research, and, especially, as she talked to others about what she was doing (following talks, informal meetings) and as she attended papers and posters at conferences or read articles. Thus, the variable "rock thickness" emerged in the course of the first field season.

Why Rock Thickness Might be Important

In the course of her fieldwork, Samantha developed a sense that rocks may be important to lizard ecology for more than the reason of constituting cover to hide from predators. Thus, towards the end of her first field season (1996), she began to develop the hunch that the thickness of the rocks under which lizards can be found plays an important role in the life of the animal.

> And then I came across this paper called "Hot rocks and not so hot rocks." And so, I didn't discover that until probably through the field season. And, so I sort of use some of the ideas out of that, and got this idea that they are probably selecting thicker rocks. Well mostly because I figured that out anyway like, this is not rocket science, I mean, you can't even touch the rocks, there's no way to living in there. (MAR 26, 1998, p. 20–21)[3]

Although she now talked about it as not being rocket science, it had taken an article about the differences in temperature variations underneath thin (0–65 °C) and thick rocks (almost constant at 24 °C for thickness larger than 40 cm) to consider thickness as relevant. In my own fieldwork, I experienced the temperature extremes both subjectively (the rocks I turned were very hot) and objectively (I measured 60 °C). Samantha cultured a gut feeling that lizards shifted the size of the rocks toward the end of her first season. It is in this context—the article and her experience in the field—that Samantha developed the sense of seasonal variations in the thickness of preferred rocks.

> I don't know if this is something that they do but I don't know the process that they do this, there's a shift from thin rocks in the spring and fall to thick rocks in the summer and

[3] The article pertained to retreat site selection by garter snakes (Huey, Peterson, Arnold, & Porter, 1989).

> I've seen, it's a clear shift. But I don't know if a lizard, that's sort of interesting, I don't know how they make that selection. (INT MAR 19, 1998, p. 37)

Importantly, scientists do not know whether something currently salient is also of interest in the scientific community. This can be established only in a broader context of the study. Thus, although distance to rock piles emerged as a plausible category, which Samantha measured for all capture sites (she could go backward making the measurements for previous captures because all sites were tagged), this variable was never mentioned in her talks, dissertation, or published papers.

Samantha also began to become attuned to the (once you know about) noticeable differences between surrounding temperatures, temperatures on the rock surface, and the temperatures underneath (thick) rocks. These temperature differences became especially salient given that lizards are ectotherms, that is, animals whose temperature is entirely controlled by environmental conditions. The following excerpts from Samantha's fieldnotes and the subsequent explanations are evidence for the emergent sense of rock thickness as salient variable.

> I went to Pat's Hill just before 9 A.M. The weather was a bit cool. We had good luck with skinks … but didn't have great luck with alligator lizards. Perhaps the alligator lizards don't come out but stay under rocks when it is too cool. (SAM JUN 19, 1997)
>
> In the rocky area near another skink site I found a male skink at 1130. It was so hot the ground temperature exceeded 50 °C! (SAM JUL 29, 1997)
>
> Basically, the hotter it is. The thing, they have sort of a preferred temperature zone that they can tolerate, there is a lethal temperature. So I was expecting to see this because it's too hot in the thin rocks. So they move to thicker larger rocks in the summer, it seems to be where they hang out. (INT MAR 26, 1998, p. 20–21)

Samantha did not first collect all the data and then conduct an analysis. Rather, during the fall and winter seasons, she completed entering all information collected into a computer database (spreadsheet from which data could be exported to a statistical package). She then ran a variety of statistical tests, even though the sample sizes were small, for example, only 16 gravid females at the end of the first season. Nevertheless, when expected (based on prior research or intuition) correlations and differences did not turn out to be statistically reliable, she began to search for possible and intuitively plausible reasons.

> There doesn't seem to be with neither rock area or rock diameter, sorry, rock thickness, there doesn't seem to be any difference between morning, afternoon and evening which is of some interest because I would have expected to see that but it doesn't seem to come out because– So, it's just like, I would expect the same pattern within the day as you would get over the season but at least it's not significant. (INT MAR 26, 1998, p. 21–22)

She ran into the problem during data analyses (winter, on campus), and then explained the interaction in terms of daily variation.

> Well the problem I've run into—It's actually not of any interest to look at it as a continuous variable because, in fact, in terms of temperatures […] you're likely to see a non-linear pattern. I don't expect that season will influence habitat in a linear fashion because spring and fall are likely to be similar and summer different. So, by hacking it into categories I figured that would eliminate that problem because everything basically peaks– there are thicker rocks in the summer and– Not necessarily, but I'm not sure, I got a little bit stuck with that. The problem is that you also get variation. So the sort of variation in two levels over the season and then variation within a day, and, so those got hacked very crude morning, afternoon and evening, (INT MAR 26, 1998, p. 16)

Samantha had not been able to detect the sought-for correlation between Julian date and rock thickness. In the context of the absent correlation, she began to think about daily variations in temperature and about the fact that the different capture times during the day had not been accounted for in her analysis. Having kept meticulous data on capture condition, including capture time, allowed her to distinguish between morning, afternoon, and evening and to enter this distinction into her models. By statistically controlling for this diurnal effect, she eventually arrived at demonstrating a significant (reliable) correlation subsequently reported in her dissertation and the published papers.

Graph and Description as Research Outcome

In the end, Samantha had spent three seasons in the field to collect the data for her doctoral dissertation, day in day out attempting to capture lizards, and then taking measurements on those caught, returning the male specimens but keeping females until after they had given birth. In the process, she and her assistants (including myself) turned hundreds of rocks everyday, big and small ones, and in cold and hot weather (one day, the temperature on top of a rock exceeded the 65 °C maximum of the thermometer). Spending so much time in the field allowed her to develop an intuitive sense with respect to things that she or the discipline did not yet know.

In both her dissertation and a published article, Samantha reported that rock thickness and rock size showed significant correlations with other variables and were important variables distinguishing different species of lizards. Thus, her emerging sense of seasonal variations in rock thickness and rock area was ultimately confirmed in a quantitative way (Figure 7). Rather than having to interpret these results, they confirmed what had already arisen as an intuition from the daily exposure to the local conditions during fieldwork. The dissertation (and published paper) stated these findings in linguistically unmediated, factual and final form, for example, as "Both rock thickness ($F_{1,171} = 5.35$, $P = 0.02$; Fig. 3.2a) and rock area ($F_{1,171} = 12.05$, $P = 0.001$; Fig. 3.2b) increased with julian date (Models 2a and 2b in Table 3.1)" (Figure 7). The statements drew support from the statistics and plots. Samantha did not draw on modifiers that are often used to mediate propositions until they can appear in their final unmediated form (Latour & Woolgar, 1979). In part, this situation may have arisen because the phenomena are directly observable and therefore are immediately plausible, intelligible, and appealing. That is, whereas after the fact it may appear as if the graphs and statistics allowed to make inferences about the natural and life history of the lizard species, Samantha was already so familiar with these animals that the statistics made sense.

Before closing this analysis, I highlight an aspect that went unnoticed to Samantha, her field assistants, supervisors, and the reviewers of the journal publication. The second graph in Figure 7 uses rock area as the dependent variable. In her publications (thesis and published article), Samantha simply wrote that she measured rock area (size) without specifying how this was done. It turns out that the measures she had collected did not allow her to determine rock size without problem.

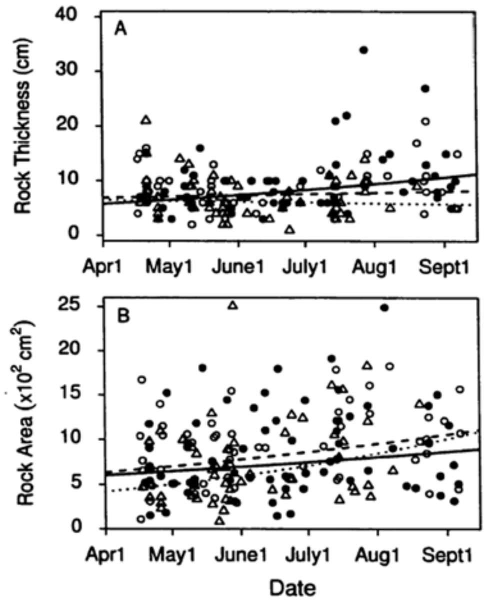

Figure 3.2: Julian date vs (A) rock thickness and (B) rock area. Regression lines are shown for juveniles (triangle, short-dashed line), adult males (open circle, long-dashed line), and adult females (closed circle, solid line) *Elgaria coerulea* from CVWMA, Creston, British Columbia collected in 1996-1998.

Retreat-site Selection
Almost all *Elgaria coerulea* used rocks as retreat sites (only 2% were captured under logs). Although rock thickness and rock area are related (R = 0.37, N = 173, P < 0.001), I tested them in separate models to determine if they were influenced by different facts. Both rock thickness ($F_{1,171}$ = 5.35, P = 0.02; Fig. 3.2a) and rock area ($F_{1,171}$ = 12.05, P = 0.001; Fig. 3.2b) increased with julian date (Models 2a and 2b in Table 3.1). Adult females and males selected rocks of similar thickness (t = 0.68, df = 173, P = 0.08) and juveniles selected the thinnest rocks (t = 2.46, df = 173, P = 0.02; Fig. 3.2a). Adult males used the largest rocks, followed by adult females and juveniles ($F_{1,171}$ = 2.58, P = 0.08). Rock thickness also decreased the capture-site temperature of lizards under rocks relative to ground temperature ($F_{1,172}$ = 2.81, P = 0.10; Model 3 in Table 3.1). Rock area did not affect capture-site temperature. (DISS, p. 34)

Figure 7. Graph portraying the relationship between the Julian date, as independent variable, and thickness and size of the rock under which captured lizards rested, on the other. (DISS, p. 44)

Samantha determined rock area in the following way. She first drew an approximate sketch of the rock as a polygon, attempting to capture the angles; she then measured each of the sides to the nearest centimeter (Figure 8). Beginning in the field lab and subsequently at home, Samantha transposed (Ψ in Figure 2) the field sketch into another polygon that in which all sides were to scale (Figure 8). She proceeded to subdivide the polygon into triangles, measured their heights, and calculated the area of each using the equation area = (base * height)/2.

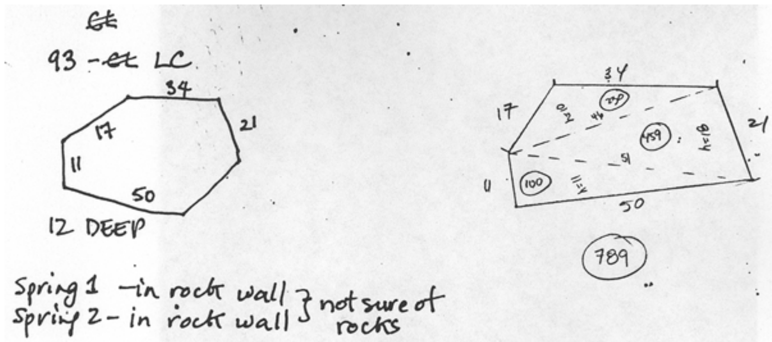

Figure 8. Record of rock size and approximate shape, based on which the area of the rock was calculated by making a scale drawing cut into triangles and rectangles, using ruler to measure the distances. (Samantha's laboratory notebook, 1996)

Basic geometric considerations show that shape and therefore area of a triangle are uniquely determined knowing the lengths of its sides—it can therefore be constructed using ruler and compass. The sides, however, do not uniquely determine the shape and therefore the area of a polygon. Many readers will have made relevant experiences: nailing four pieces of wood or using pins to fasten four pieces of straw will result in a quadrilateral that does not maintain its shape and has to be fixed using a brace. Thus, each polygon could have been constructed differently—Figure 8 already shows that Samantha sometimes departed considerably from the angles in her original sketch (e.g., the angle between the 11- and 50-centimeter sides).

Graph as Metonymic Representation of Research Process and Outcome

This study was designed to understand scientists' graph-related competencies, and in particular, to understand the underpinnings of their competencies in talking about familiar graphs (from their own or related work). My analyses showed that Samantha had trouble correctly interpreting even the most basic type of graphs in her field (often one of the first graphs students encounter in an introductory ecology course). At the same time, talking about her own graph brought out the intimate familiarity Samantha had with the natural world of her alligator lizard species. I then rallied evidence from my three-year ethnographic effort to articulate the co-emergence of symbolic elements and structures (variables, measures, statistics, graphs) and Samantha's embodied understanding of the natural environment in which the represented animals are a part.

There were many instances when Sam elaborated a formal graph that resulted from her data in terms of her "anecdotal" knowledge that resulted from her fieldwork. That is, Samantha's knowledge of the field sites provided a justification of and a sense for the results of the statistical analysis. In the interview excerpts, Samantha talked about the statistically significant differences between dependent variables according to the geographical site where she had captured her lizards. Samantha's work includes, to paraphrase Garfinkel et al. (1981) as an identifying detail of it, its natural accountability, which in turn permits pointing to what her work was discovering: the relationship between Julian date, on the one hand, and rock surface size and rock thickness, on the other. In her dissertation, then, this work is rendered as the property of the natural history of this alligator lizard species. The relationship between research process and context, on the one hand, and the graphically depicted correlations, on the other, was made clear time and again in the course of my research:

> But even when you control for the effect of site there are differences among season which is, which is, and there're expected, it's not very, there's nothing shocking which is good, I don't like shocking things. (INT MAR 26, 1998, p. 20)
>
> Site is significant in just about everything, which is not, to me, at all surprising knowing these sites. The only thing it's not different in, that is not important, is the nearest rock. But it is important, it's important in everything and to me it's not, it's not surprising knowing what the sites look like. (INT MAR 26, 1998, p. 28)

Twice in this excerpt Sam noted that her finding statistically significant differences was not surprising given what she knew about the sites. That is, her knowledge about the sites, which she articulated in terms of what she elsewhere called "anecdotal knowledge," that is, the structures of local detail surrounding the data collection, made statistical differences not surprising. But of course, she acquired this anecdotal knowledge in the course of her fieldwork long before she ever conducted the statistical analyses during the winter season back on home campus.

Much as in a study of sociology graduate students interpreting hospital records (Garfinkel, 1967), the scientifically oriented readers of familiar graphs in my studies overwhelmingly arrived at definite conclusions about what the graphs say by drawing on their existing understanding of the natural world and what actually and possibly might happen in it. That is, scientifically oriented readers of graphs did not so much *make inferences from* representations but articulated existing understandings, which they therefore *brought to* the representation. The perceptual presence of the representation merely *occasioned* the talk about the graph. It is for this reason that the function Φ_2 linking symbolic and natural worlds has to be bi-directional (Figure 2).

Whereas the relationship between talks, representations and the natural world is bi-directional, the graphs in Samantha's dissertation and publications were also the result of a three-year research effort. Once completed, the graphs pointed back to the process and context of their own construction. We can therefore say that Samantha's graphs bear a metonymic relationship to the process and context that brought it about. It is not that Samantha merely produced graphs but that her familiarity with the production process and context provided her with resources to underscore the plausibility of the displayed relationship. That is, the structures on both sides of Figure 2 co-emerge and, in fact, constitute one another; the structuring processes Θ_s and Θ_d are mutually constitutive and therefore reified one another. Some dimension (distance to nearest rock, rock area, rock thickness) that emerged in the lifeworld of Samantha was articulated as a variable and was subsequently reified during statistical analysis; on the other hand, her statistical analysis was reified when it was intelligible in terms of her lifeworld experiences. In other words, there is a dialectical relation Φ between mathematical and lifeworld structures as expressed in Figure 2 rather than the one-directional relation expressed in Figure 1. Inquiries and the objects they produce are indeed intertwined creatures. The graph as a worldly object emerged itself from an intertwining of natural objects and embodied practices.

Using the case of rock area, I showed how a practice questionable from a mathematician’s perspective nevertheless went unnoticed in ecology context within which Samantha conducted her work. This potentially raises doubts about the reliability of the results she reported in and contributed to the literature. However, such observations do not add to the understanding of science. For the discussion at hand, the ecologist’s work of finding rock surfaces was taken as practically adequate way for constructing the quantity. The ultimate result of the statistical analyses made sense from the perspective of the researcher who spent a major part of three years capturing animals, experiencing the local conditions, and articulating some of them in terms of objective measurements. It is therefore immaterial that the triangle heights were measured in drawings rather than on the natural object or that a few lines of arithmetic would have yielded a formula for calculating the area of a triangle from the length of its sides, a formula which could easily be embedded in a spreadsheet, would have infinitely reduced the work of finding areas and increased the precision of the result. Determining the area of the rock is not something for which the ecologist has to provide an account for us, but which Samantha had to account for when she reported her results in her thesis and publications. Her methods and calculative techniques obtained their efficacy, adequacy, and legitimacy in the embodied and socially organized praxis of her discipline, which accepted what she had done by conferring a degree and publishing her paper.

Coda

The purpose of this paper was to show how the structuring of the phenomenal world is associated with and provides the grounds for a structuring of the symbolic world. That is, any correlations and differences—or the absence thereof—are understood in terms of what makes sense in the phenomenal world. This study raises questions about some of the assumptions about generalizations that underpin cognitive science research. Thus, models of graph interpretation based on the analysis of think-aloud protocols where scientists interpret familiar graphs do not explain why competent scientists misinterpret even simple but unfamiliar graphs in their own domain. The present cognitive anthropological study of graphing instead suggests that familiarity with the setting—natural environment and tools and practices to represent it—are an integral part of competence with respect to a particular graph.

Acknowledgments

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